Relationship of Footstrike Pattern and Landing Impacts During a Marathon

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Abstract (275 words max for MSSE)

Purpose: Foot strike patterns influence landing mechanics, with rearfoot strike (RFS) runners exhibiting higher impact loading than forefoot strike (FFS) runners. The few studies that included midfoot strike (MFS) runners have typically grouped them together with FFS. Additionally, most running studies have been conducted in laboratories. Advances in wearable technology now allow the measurement of runners' mechanics in their natural environment. The purpose of this study was to examine the relationship between foot strike pattern and impacts across a marathon race.

Methods: 222 healthy runners (119 M, 103 F; 44.1±10.8 years) running a marathon race were included. A treadmill assessment was undertaken to determine foot strike pattern (FSP). An ankle mounted accelerometer recorded tibial shock (TS) over the course of the marathon. TS was compared between RFS, MFS and FFS. Correlations between speed and impacts were examined between FSPs. TS was also compared at the 10km and 40km race points.

Results: RFS and MFS runners exhibited similar TS (12.24±3.59g vs. 11.82±2.68g, $p=0.46$) that was significantly higher ($p<0.001$ and $p<0.01$, respectively) than FFS runners (9.88±2.51g). Additionally, TS increased with speed for both RFS ($r=0.54$, $p=0.01$) and MFS ($r=0.42$, $p=0.02$) runners, but not FFS ($r=0.05$, $p=0.83$). Finally, both speed ($p<0.001$) and TS ($p<0.001$) were reduced between the 10km and 40km race points. However, when normalized for speed, TS was not different ($p= 0.84$).

Conclusions: RFS and MFS exhibit higher TS than FFS. Additionally, RFS and MFS increase TS with speed, while FFS do not. These results suggest that the impact loading of MFS is more like RFS than FFS. Finally, TS, when normalized for speed, is similar between the beginning and end of the race.

KEYWORDS: Running, biomechanics, acceleration, speed, fatigue, tibial shock

Introduction

Impact loading during running has received significant attention recently (1,2,3,4), especially as it pertains to footstrike patterns. Up to 95% of runners exhibit a rearfoot strike pattern (RFS), landing on their heel first (5,6,7). The remainder are midfoot strike (MFS), landing with a flat foot, or forefoot strike (FFS), landing on the ball of their foot. A RFS pattern is typically associated with an abrupt impact force transient that is associated with an increased force load rate above that of a FFS pattern (4). Increased load rates are of interest as they have been associated with a number of common running-related injuries in RFS runners (8,9,10). In further support of this, Daoud, et al, reported that RFS runners had an approximately twofold higher overall injury rate when compared to FFS runners (11).

While the impact mechanics of RFS and FFS runners are well known, less is known about MFS mechanics. As a general rule, most studies have grouped MFS together with FFS runners (1,12,13,14) as they are both non-heelstrike patterns. However, one study by Jamison et al (15), assessed MFS patterns separately from RFS and FFS patterns. These authors reported that vertical load rates progressively increased from RFS to MFS to FFS patterns, although RFS and MFS patterns were not significantly different from each other. These results suggest the combining MFS and FFS runners together may need further consideration.

The measurement of vertical load rates associated with different strike patterns requires the use of force plates. However, measures of TS from bone mounted accelerometers have been strongly associated with vertical load rates from force plates with correlations of r=0.97 (16,17). Studies of skin mounted accelerometers have reported lower, but still strong, correlations of r=0.70 (18).

Therefore, TS has been considered a reasonable surrogate for vertical load rates when a force plate is not available.

Both vertical load rates (19) and TS (20,21,22) have been consistently reported to increase with fatigue. Clansey, et al, found a 20% difference in vertical loading rate from the beginning to the end of an exhaustive run (19). Another study by Derrick, et al, also saw 20% increase in TS during an exhaustive run set at 3200m maximal effort pace (21). Mizrahi saw a large 46% increase over the course of a 30-minute exhaustive run. However, these studies have been conducted on a treadmill and for 15-20 minute high intensity runs. One study by Garcia-Pérez et al. did examine differences in fatigue when running was performed on a treadmill versus overground (28). Immediately following a 30 min. run at 85% of each runners max aerobic speed, TS was measured in each condition. These authors noted that TS reduced by 2 gs (10%) running overground and increased by 2 gs (12%) when running on a treadmill, although these changes did not reach significance.

Running at different speeds has long been shown to have a relationship with ground reaction forces. Hamill, et al, showed a positive relationship with peak ground reaction forces in runners running at four different speeds (23). Using a regression analysis, Munro, et al, found all of the ground reaction force variables of interest (both vertical and anteroposterior) to be speed dependent (24). While studies have been shown ground reaction force variables, such as loading rate, to correlate with acceleration (16,17,25), few studies have examined the relationship of TS and speed. One study by Brayne, et al, reported a positive relationship between speed and TS (26). Additional research would strengthen the relationships being found between speed and TS.

Most studies of tibial shock, to date, have been conducted in laboratories (20,21,22) which do not truly mimic a runner's natural environment. Now that accelerometers have been incorporated into wearable sensors, tibial accelerometer measures can be taken from the laboratory onto the roads or trails. However, to date, only one study has done so. Giandolini et al monitored the tibial accelerometry of a single runner during a 45 km trail race (27) to estimate the variation in FSP.

In summary, the relationship between footstrike strike pattern and landing impact has not been extensively examined in runners' natural environment, which motivated the following aims. We first aimed to compare landing impacts quantified by tibial shock, between RFS, MFS and FFS runners during a marathon race. We hypothesized that FFS runners would have lower landing impacts than MFS runners, who would have lower impacts than RFS runners. We also examined the relationship between tibial shock and speed across FSPs. We expected that landing impacts would increase with speed across all FSPs. Additionally, we were interested in the effect of fatigue on impacts and hypothesized TS would increase later in the race with fatigue. Finally, running studies often depend on recruitment of subjects based upon *their self-reported* footstrike pattern. Therefore, as a secondary question of the study, we sought to determine the accuracy of self-reported FSPs.

Methods

Participants

Subjects were recruited from the registrants of a 2016 marathon race. To be included, they had to be at least 18 yrs. of age, currently uninjured, and not have any known medical conditions that affected sensory or motor function, inhibited balance, or altered gait. Over 800 runners volunteered for the study and participants were chosen to provide a balance of runners across sex, age and expected race times and self-reported FSP. As up to 95% of runners have been reported to be RFS (7), MFS and FFS runners are more difficult to recruit. Therefore, we accepted all runners reporting to be FFS and MFS to increase the numbers in these groups. Resources limited our maximum subject number recruitment to 300. Of these 300 offered to participate, 46 of the runners declined prior to consent due to injury, lack of interest and withdrawal from the marathon. As a result, 254 healthy runners between the ages of 18-74 yrs. were consented for this study. On race day, two of these chose not to wear the device, 16 reported loosening the device, and 2 removed the devices during the race. Therefore, these 20 participants were excluded. Additionally, 9 participants reported pain during the race of 3/10 on a visual analog scale and were excluded due to potential gait compensations for the pain. Three were later excluded through an outlier analysis. Therefore, the 222 remaining runners (119 M, 103 F; 44.1±10.8 yrs.) comprised the study group (Figure 1). The study was approved by the Institutional Review Board and all participants provided informed consent prior to entering the study.

Protocol

Three months prior to the pre-race orientation session, participants completed a survey regarding their running mileage and running injury histories. They were also asked to self-report their foot strike pattern. The orientation session occurred at the race expo 1-3 days before the marathon. During this time, runners received individual instruction and practice on proper application of the accelerometer device (IMeasureU BlueThunder IMU, Auckland, New Zealand; Dimensions: 40mm x 28mm x 15mm; Weight: 12g; Figure 2a) for race day. The location for the device placement was marked on the antero-medial aspect of their right distal tibia with an indelible marker (Figure 2b). The strap that secured the device to ankle was marked with a line to denote how tightly to secure it on race day. Identification numbers were written down the lateral side of the right lower leg in indelible marker so that runners could be identified on video during the race.

In order to determine habitual footstrike patterns, each subject ran on a level treadmill for 3 minutes at a self-selected speed to familiarize with treadmill running. The speed was then increased to 90% of each subject's projected race speed. Participants were then filmed running at 240 frames per second with a video camera (Exilim EX-100, Casio, Tokyo, Japan) to determine their habitual FSP (Figure 2c). While the video data were collected, a Stroop distraction test was administered to minimize the risk of performance bias. In this test, runners are presented with columns of words describing colors, such as red, blue, yellow, etc. However, the color of the word does not match the text. For example, the word 'red' may be printed in blue, 'blue' may be printed in green and 'yellow' may be printed in orange. The runner was asked to read aloud the *color* of each of the words, not the text of the words. This was done to reduce the runner's concentration on their running pattern. Runners who landed on their heel first were classified as RFS, those who landed on the ball of their foot first were classified as FFS and those who landed with a flat foot, were classified as MFS. Five footstrikes were analyzed. As the patterns sometimes varied within a trial, the runner was classified with the pattern that was present in at least 3 of 5 footstrikes.

On the day of the race, each subject attached the accelerometer to their distal tibia as instructed during the orientation. Accelerometers began recording at 1000 Hz when switched on and recorded continuously for the entire race. Only the tri-axial accelerometer component of the inertial sensor was used, as this allowed for increased sampling rate and battery life. FSP was recorded with the same video camera that collected their FSP on the treadmill. One camera was placed at the 10k mark and the other at the 40K mark, as these locations had relatively flat gradients (less than +/- 1 degree on average). Cameras were placed on a tripod approx. 15 cm high and was recording continuously at 240 frames/second throughout the race. Accelerometers were collected by study staff at the finish line. Devices that weren't collected immediately at the finish line were mailed back using self-addressed stamped envelopes provided by the study staff. 5km time splits and finish times publicized from the race were used for the analysis.

Data Processing

Raw acceleration data were downloaded from each device and processed using a custom Python program to Python 2.7. As the vertical axis of the accelerometer was closely aligned with the long axis of the tibia, this component of the acceleration signal was used for each right footstrike and defined as TS. Since impact peaks contain high frequency signal, these data were not filtered so as to retain the magnitude of the peak values. Peaks which were 2.5 times or greater than the standard deviation from the mean, were considered noise and were removed.

Clipped data that exceeded the 16g limit for the accelerometer were interpolated using Pandas 0.23.2 in Python 2.7. This was done using a 5th order spline interpolation using 3 data points on each side of the clipped portion of data. A sample plot of the algorithm is provided in Supplemental Digital Content 1, Accelerometer Interpolation Plot. This interpolation algorithm was tested by randomly selecting from 10 subjects whose mean impacts for the entire race were close to 16g. From these data, we chose all vertical acceleration peaks between 15g and 15.9g, and removed the data above 15g. The peaks were re-calculated using the interpolation algorithm. Since the analyzed peaks were within the operating range of the sensor, the calculated peak could be compared to the actual peak. In all, 18,708 peaks across the 10 subjects were analyzed. On average, peaks were found to be underestimated by 0.02g (+/- 0.24g). Thus, we concluded that this method was sufficiently accurate to identify these peak accelerations (please see Supplemental Digital Content

2, Interpolation Support, for a more detailed analysis of our validation technique). While some peaks were overestimated, the vast majority of peaks were slightly underestimated. When looking at different FSP, RFS had the most peaks interpolated (10km: 24.8%, 40km: 13.4%, followed by MFS (10km: 16.3%, 40km: 8.3%), and finally FFS (10km: 5.0%, 40km: 1.5%). Only 14.5% of peaks were interpolated across all runners, with the majority of runners (64.4%) having less than 10% interpolated. Additional analysis of the prevalence of peak interpolation across all FSP and distances can be found in Supplemental Digital Content 3, Interpolation Summary.

The video data were observed independently by two members of the study staff. These observers were blinded to the habitual pre-race pattern of these runners tested at the expo. Staff first looked for runners with the numerical identifiers on the side of their right lower leg. If the foot strike was clear and unobstructed, then the FSP was classified as described earlier. Due to the field of view, only one footstrike per runner was classified.

Variables and Statistical Analysis

Prior to statistical analysis, a median outlier detection method was used to assess and remove outliers (30). Data were then analyzed in SPSS (v.22; IBM, Armonk, NY). All data were tested for normality using a Shapiro-Wilk test. Normality was confirmed, thus parametric tests were applied.

Independent t-tests were used to assess for differences in TS between FSP ($p<0.05$). For each FSP, a regression analysis was used to determine the interaction of TS and speed using individual runner's TS_{10} data points and then compared to each other FSP. An ANOVA was used to assess significance of the regression and FSP group linear regression gradients, 95% confidence intervals (CI), and r values were also reported.

To assess the effect of fatigue, TS was averaged over an early and late part of the marathon race. Average TS between the 5km and 10km points was calculated and referred to as TS_{10}. Average TS was also calculated over a late part in the marathon race from 35km to 40km and referred to as TS_{40}. These sections were selected since they had relatively flat gradients (less than +/- 1 degree on average). TS for all subjects (n = 222) was evaluated at both these points. To account for the influence of speed, average TS was normalized by average speed ($g/m \cdot s^{-1}$) that was obtained from the publicized 5 km time splits to obtain TS/Speed values. This was done for both TS_{10} and TS_{40km}.

Paired t-tests were used to compare 5 kilometer increments points from early course TS at 10km (5k-10k, TS_{10km}) and late course TS at 40km (35k-40k, TS_{40km}) for all 222 subjects. Descriptive comparisons were made between self-reported FSPs and the pre-race FSPs. Finally, comparisons of pre-race FSPs with those observed at the 10km and the 40km mark were assessed descriptively.

Results

The FFS runners exhibited significantly lower TS than MFS and RFS runners at the 10km race point (Figure 3). The pre-race video analysis of habitual FSP revealed that our population included 169 RFS, 31 MFS and 22 FFS runners. While FFS had lower TS than MFS and RFS, there was no difference between RFS and MFS runners (*P=0.49)*. The analysis of the relationship between TS and speed revealed a positive significant relationship for RFS and MFS and no relationship for FFS (Figure 4). Specifically, the RFS group exhibited a gradient of 4.69 (r=0.54, p=0.01, 95% CI = 3.57 and 5.81). The MFS group exhibited a lower gradient of 2.58 (r=0.42, p=0.02, 95% CI =

0.47 and 4.69). However, the FFS group demonstrated a gradient of 0.23 ($r=0.05$, $p=0.83$, 95% CI = -1.92 and 2.37).

When assessing the effect of fatigue on impacts across all runners, TS significantly decreased between the 10km and 40km points in the race (Table 1). However, speed also significantly decreased between these points. When TS was adjusted for speed (TS/Speed) no significant difference was found.

In order to assess the validity of our FSP classification in the field, we compared the FSP recorded at the expo prior to the race to those FSPs measured in the field. Only 92/222 FSPs were identified at the 10km point and 123/222 were identified at the 40 km point in the race. This was due to the obstructions from other runners, illegible identifier numbers and footstrikes that missed the field of view of the camera. Of those captured at the 10km point, 75% (69/92) demonstrated FSPs that agree with their expo data. Of those observed at the 40 km point 76% (93/123) runners demonstrated FSPs that agree with their expo data. Of the 65 runners captured at both locations, 51/65 (78%) and 53/65 (82%) agree with their expo FSP at 10km and 40km, respectively. In total, agreement was moderately strong.

For our secondary question, only 39.1% of all runners correctly reported their FSP (Table 2). RFS runners were the least accurate with only 30.7% being correct. MFS and FFS runners had a higher accuracy rate with 64.5% and 68.2% correctly identifying their FSP.

Discussion

The purpose of this study was to examine the relationship between FSP and TS in a runner's natural environment during a marathon race. Specifically, we sought to compare TS in habitual RFS, MFS and FFS runners. We also aimed to examine the relationship between speed and TS across differing FSP. Additionally, we explored how TS changes with fatigue. Finally, we were interested in knowing how accurately runners perceive their own FSPs.

In contrast to our expectation, we found that MFS runners exhibited significantly higher TS than FFS. Additionally, MFS and RFS runners exhibited very similar TS values. These findings challenge the common practice of grouping MFS and FFS runners together when assessing impacts (1,12,13,14). As TS in MFS is significantly higher than FFS, combining these two groups of runners will confound study results. There is a dearth of information regarding impact loading in MFS runners. However, a study by Jamison et al. (15) has supported our findings with reports that MFS patterns are associated with higher vertical load rates than FFS patterns. Additionally, they reported that the vertical load rates of MFS patterns were statistically similar to RFS patterns. These results suggest that MFS should ideally be analyzed separately, and if grouping them together, should be combined with RFS rather than FFS.

We postulated that TS would increase with speed across all FSPs. As expected, tibial shock did increase as speed increased across the RFS runners, suggesting harder landings with higher speeds. This increase was consistent with a prior study (26) examining RFS runners. MFS runners also demonstrated a significant relationship between speed and TS. However, FFS runners exhibited very similar mean TS values across a broad range of slow to fast speeds (between 2m/s and 5m/s). This lack of increase in TS implies that FFS runners are able to modulate their TS regardless of changes in speed. This is likely a function of increasing calf musculature activation to assist with dampening of the impacts as speed increases. The similar relationship between speed and TS for the RFS and MFS further supports our previous suggestion that these two FSP are similar in terms of impact loading characteristics.

We also anticipated that TS would increase with fatigue as indicated by TS_{40} being greater than TS_{10}. This was based upon previous treadmill studies that documented increases in TS with fatiguing runs (20,21,22). However, in these studies, the runs were shorter and more intense and the treadmill speed remained constant throughout the run. Our results are similar to those of Garcia and Perez who noted a 10% decrease in TS after fatigue. When running overground, individuals are able to vary their speed which helps them pace themselves. This is particularly important with endurance events such as a marathon. TS decreased by about 15% in our study, which is slightly larger than that reported by Garcia-Perez et al. (28) perhaps due to a higher level of fatigue following the marathon. However, in our study, speed also reduced by approximately 15%. When we normalized TS for speed, we found no difference between TS_{10} and TS_{40}. This suggests that when runners are free to modulate their speed, they may be able to prevent some of the mechanical effects of fatigue by slowing down, even when running marathon distances.

Our results suggest that self-report of FSP is not very accurate. Overall, only 39.1% of these runners were able to accurately self-identify their FSP. This is lower than previous values (between 49.5-68.2%) that have been reported in the past (29,12). This may be due to a couple of factors. First, runners in our study self-reported their FSP on a survey they completed months prior to the race, rather than just prior to the testing. Additionally, previous studies did not use a distraction test during the video assessment of the FSP. This may have led to a performance bias by runners trying to run with the FSP that they had reported thereby increasing the self-report accuracy. The Stroop test was effective in adequately distracting the runner from their mechanics, but was not so distracting that runners became unsafe on the treadmill. RFS runners were least accurate of the FSP groups, with only 30.7% accurately reporting a RFS pattern. Most RFS runners believed they were running with a more anterior strike pattern. MFS were approximately half as accurate as the RFS runners When wrong, they also were likely to report a more anterior FSP (i.e. FFS). FFS runners were the most accurate, accurately reporting a FFS pattern 68.2%, but a MFS pattern 31.8% of the time. This suggests that it may be easier to perceive a FFS compared to either a RFS or a MFS. These results indicate that self-reporting FSP may be even less accurate than previously thought. Results also confirm that video analysis, over self-report, should be used to establish habitual FSP, and that perhaps a distraction test should be incorporated.

The acceleration range of the sensor used was a limitation of our study. All TS values above 16g were estimated using a custom interpolation algorithm and therefore should be considered as approximate magnitudes of peak TS. However, when testing peaks between 15g and 15.9g, our algorithm underestimated peak values only 0.02g (+/- 0.24g). Furthermore, a supplemental analysis of the number of peaks requiring interpolation supports our conclusions that FFS runners land more softly than MFS or RFS runners (Supplemental Digital Content 3, Interpolation Summary). Nonetheless, tibial accelerometers that include ranges higher than 16g are recommended for future studies where precise TS values are needed.

In summary, this is the first known largescale study to date that has measured impact loading in a runner's natural environment. It is also the first to assess these impacts across natural RFS, MFS and FFS runners. Finally, it is the first to assess how these impacts change over the course of a marathon. Our findings suggest that MFS runners exhibit similar impacts as RFS, and both exhibit higher impacts than FFS. RFS and MFS both exhibit increasing impacts with increasing speed, while FFS runner's do not. These results together imply that RFS and MFS runners are similar in their impact loading and that a FFS pattern may be protective against increasing impacts with increasing speeds.

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Figures:

Figure 1: Flow diagram of subjects excluded from the study

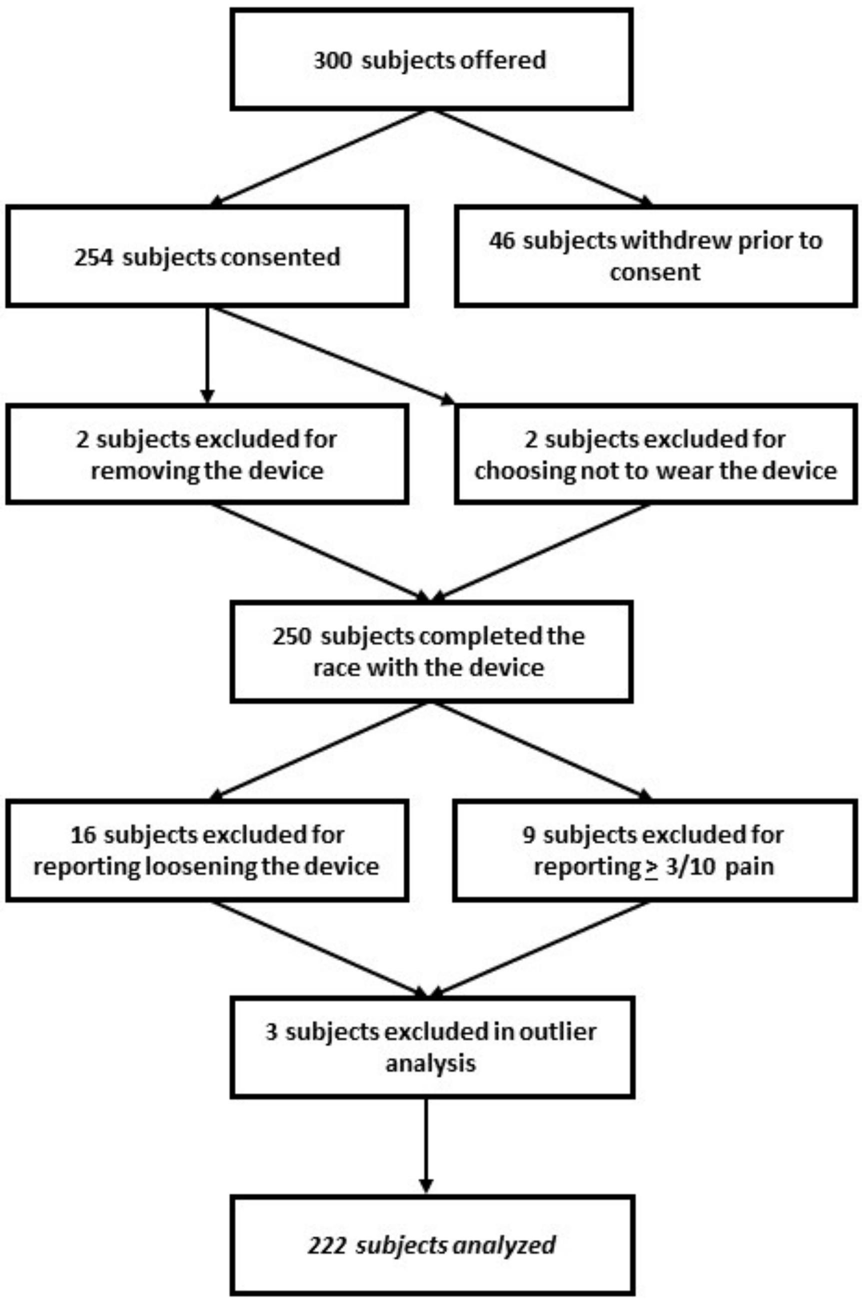


Figure 2: A. the IMU device. B. Attachment of the IMU to the distal medial tibia. C. Collection of the footstrike pattern of a runner at the pre-race expo.

Figure 3: Comparison of TS for each landing pattern at 10 km. * denotes P=0.01

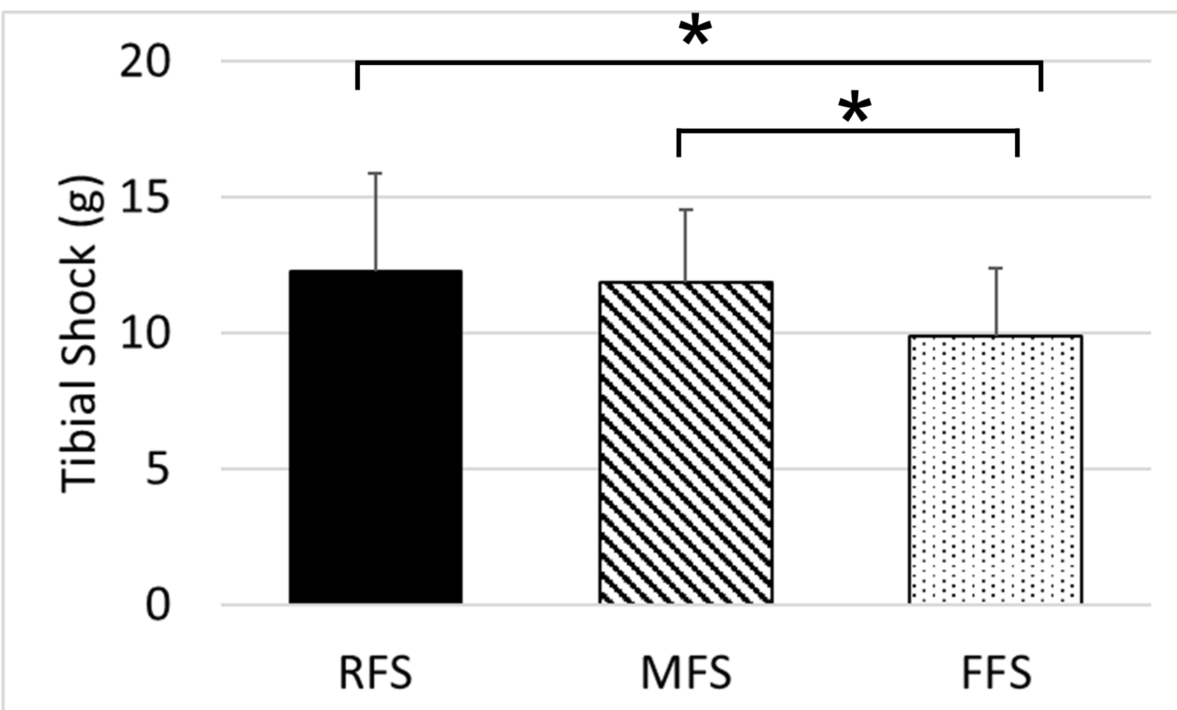
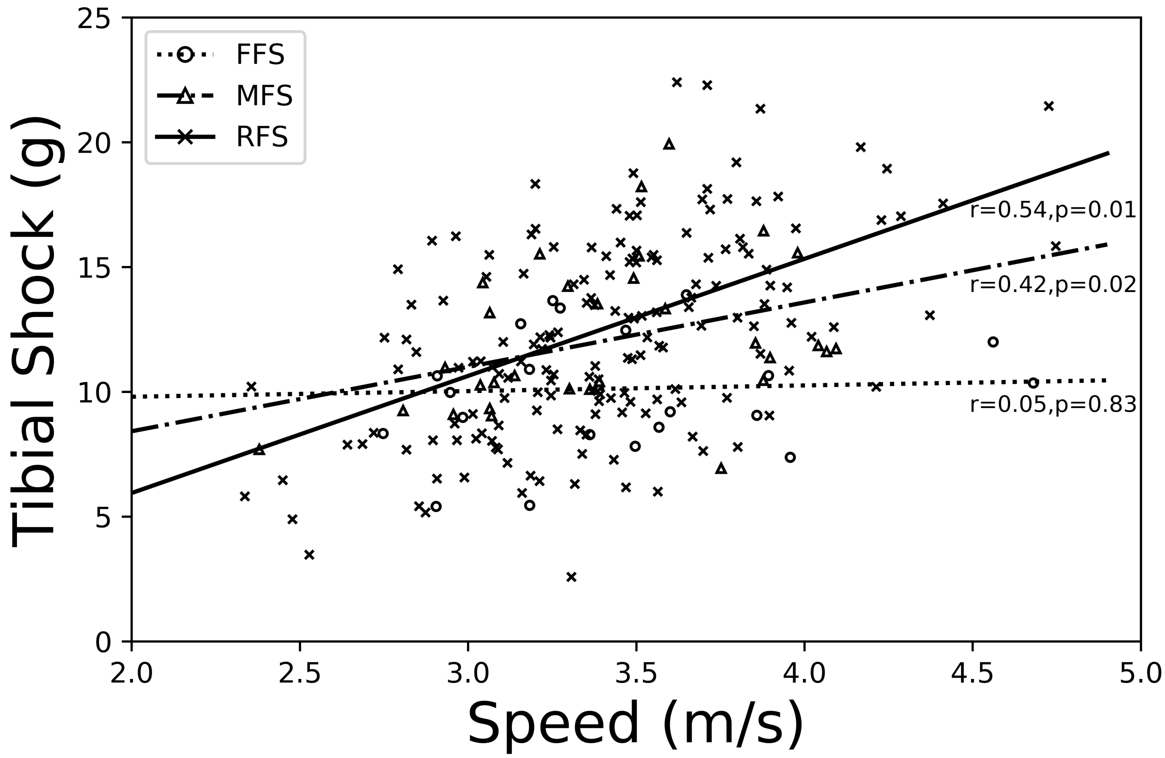


Figure 4. Relationship between TS and speed for each FSP. A significant correlation was noted for the RFS and MFS, but not the FFS.



Tables:

Table 1: Comparison of TS (non-normalized and normalized to speed) between 10km to 40km

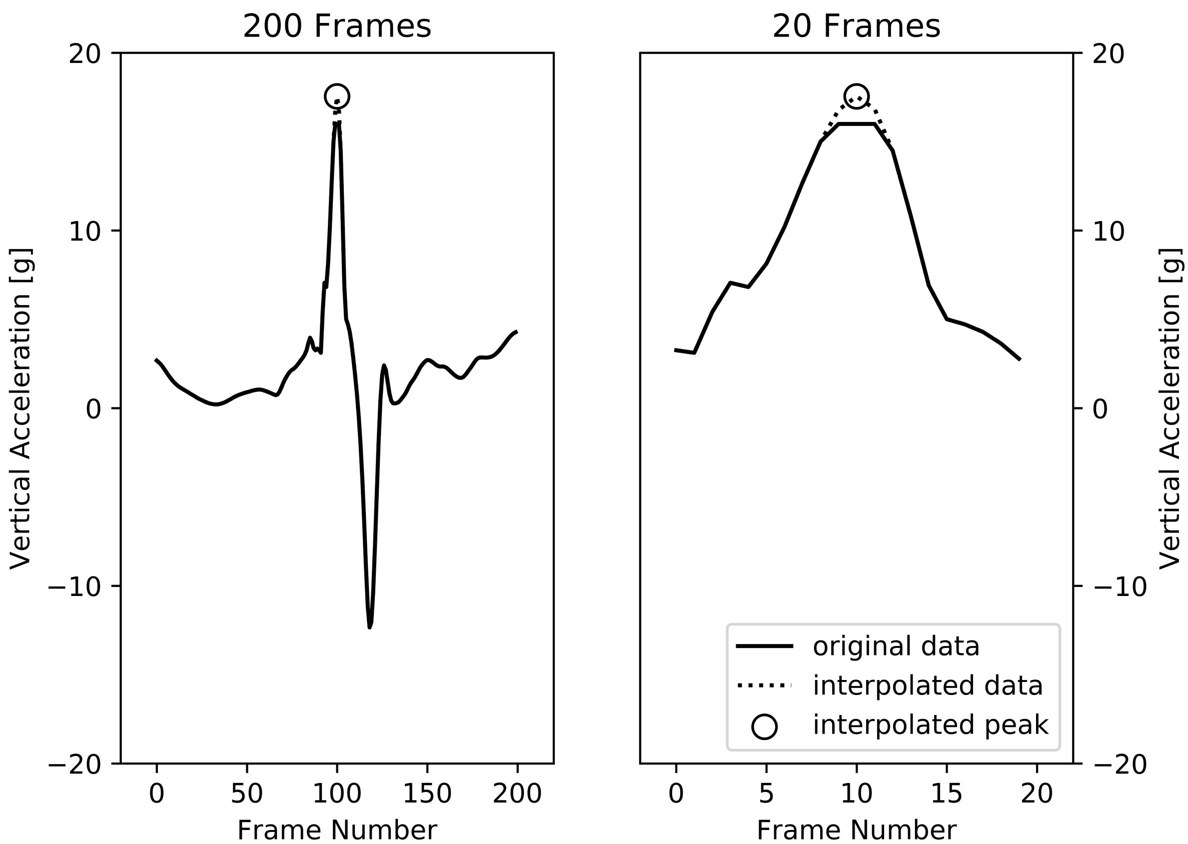
	10km	**40km**	**p**
TS (g)	11.94 ± 3.70	10.19 ± 3.40	<0.01
Speed ($m \cdot s^{-1}$)	3.41 ± 0.45	2.92 ± 0.52	<0.01
TS/Speed($g/ m \cdot s^{-1}$)	3.50 ± 0.97	3.46 ± 0.92	0.84

Table 2: Self-reported FSP Accuracy

	RFS	MFS	FFS	ALL
Measured FSP	169	31	22	222
Self-Reported FSP				
RFS	**52**	1	0	53
MFS	84	**20**	7	111
FFS	22	10	**15**	47
Don’t Know	11	0	0	11
Number correct	52/169	20/31	15/22	87/222
% accuracy	30.7%	64.5%	68.2%	39.1%

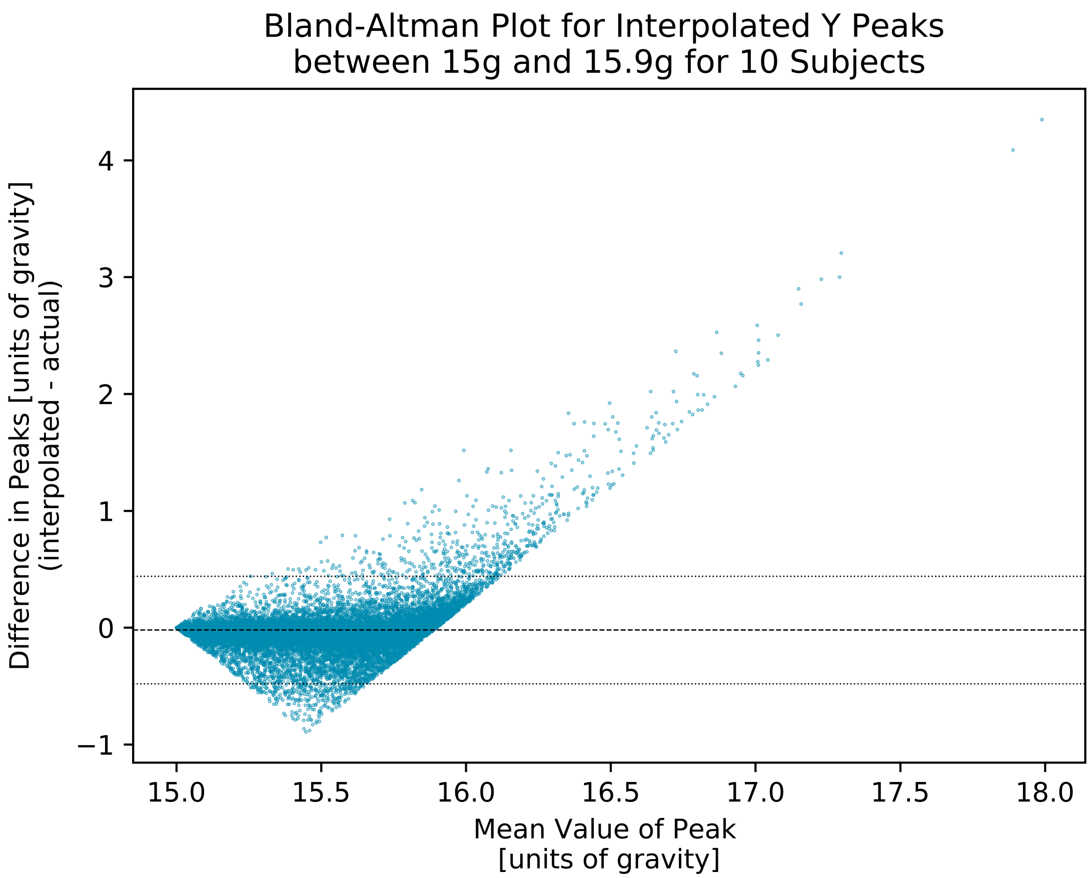
Supplemental Digital Content 1: Accelerometer Interpolation Plot

SDC Figure 1: Example plot of an interpolated peak with 200 frames of surrounding data (left) and 20 frames of supporting data (right). The solid line in each represents that data recorded by the device, while the dotted line indicates the interpolated section. The circle indicates the point of the interpolated peak.

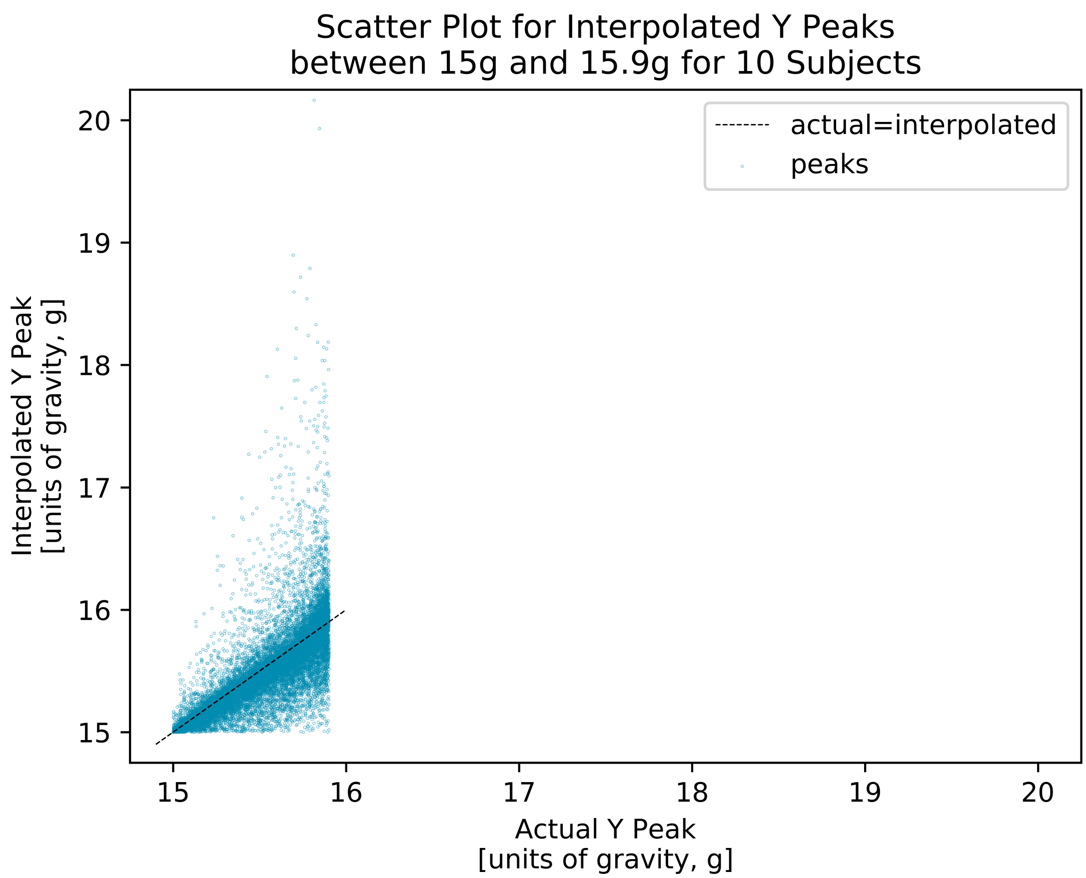


Supplemental Digital Content 2: Interpolation Algorithm Validation Support

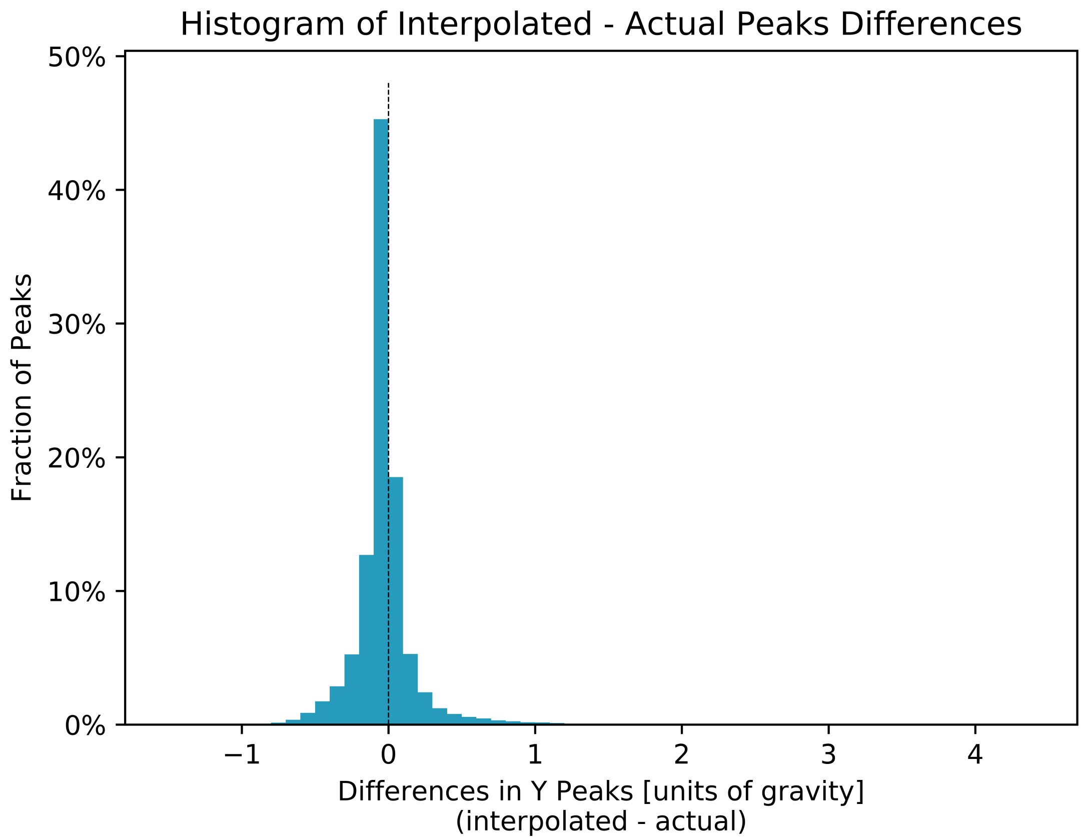
SDC Figure 2a: Bland-Altman plot. Each point represents 1 of the 18,707 peaks used in the validation. The horizontal axis represents the mean of the actual and interpolated peaks. The vertical axis is the difference between interpolated and actual peaks, with negative values indicating an interpolated peak being lower than the actual peak. Dotted lines represent 95% confidence interval [0.44g, -0.48g]. Dashed line represents the mean difference [-0.02g]. The shape of the data is a result of the algorithm's design and the constraints on the peaks used in the analysis. First, our interpolation algorithm would was prohibited from estimating a peak below 15g. Also, the distribution of peaks used in the analysis were not normally distributed within the 15g-15.9g range.



SDC Figure 2b: Scatter plot ofthe 18,707 actual (horizontal axis) and interpolated (vetrical axis) peaks used in our analysis. The dashed line represents perfect agreement. Axes are scaled identically.



SDC Figure 2c: Distribution of interpolated peak differences. The horizontal access is the difference between interpolated and actual peaks, with negative values indicating an underestimation of peak values. Bins are 0.1g wide. The vertical axis is the percent of peaks in the bin. Dashed vertical line indicates perfect agreement.



Supplemental Digital Content 3: Interpolation Summary

SDC Table 1: Summary of interpolation prevalence by FSP and race segment is presented below for all subjects analyzed. MEAN is the mean of all subject's percentage of peaks interpolated (so for the RFS during the 5-10k section, it's a mean of 169 values). AGGREGATE is the total number of peaks interpolated divided by the total number of steps taken for all subjects in the FSP group during that section of the race. This analysis indicates RFS runners have more peaks interpolated than MFS (which is second) and FFS (which has the fewest peaks interpolated).

5-10k (early race)	**RFS**	**MFS**	**FFS**
Subjects	169	31	22
Mean	24.8%	16.3%	5.0%
Aggregate	23.2%	15.9%	5.3%
Interpolated Peaks	84460	10726	2470
Total Peaks	364106	67625	46889
35-40k (late race)	**RFS**	**MFS**	**FFS**
Subjects	163	31	21
Mean	13.4%	8.3%	1.5%
Aggregate	12.1%	7.8%	1.5%
Interpolated Peaks	48114	5929	774
Total Peaks	398644	75665	51591

SDC Figure 3: Distribution of subjects by the percent of peaks interpolated for early race (left) and late race (right) distances. The horizontal axis represents the percentage of TS values interpolated for the given race section, in 10% bins. The vertical axis indicates the percentage of subjects in each bin. Color and bar outline represent FSP. For all foot FSPs, the majority of subjects had less than 10% of their TS values interpolated. Still, the FFS group has the highest proportion of subjects having between 0-10% of their TS values interpolated. The MFS group is the only group to have less runners in the lowest interpolation frequency bin at late race compared to early race distances.